BNL-77928-2007-IR

Report on Atomization Tests for Project Titled "Biodiesel Blends in Microturbine"

C. R. Krishna

January 9, 2007

Energy Sciences and Technology Department/Energy Resources Division

Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

DISCLAIMER

Introduction

The injectors for the Capstone turbine have the general design shown in figure 1 below [1]. It consists of an airblast atomizer with a cylindrical fuel nozzle and an annular air passage surrounding it. The airblast atomizer is surrounded by a 'mixing tube' with circular holes just downstream of the atomizer outlet and swirler holes further downstream. During operation, these holes bring 'hot' air/gases to help vaporize and provide premixed fuel and air for combustion downstream of the 'mixing' tube.

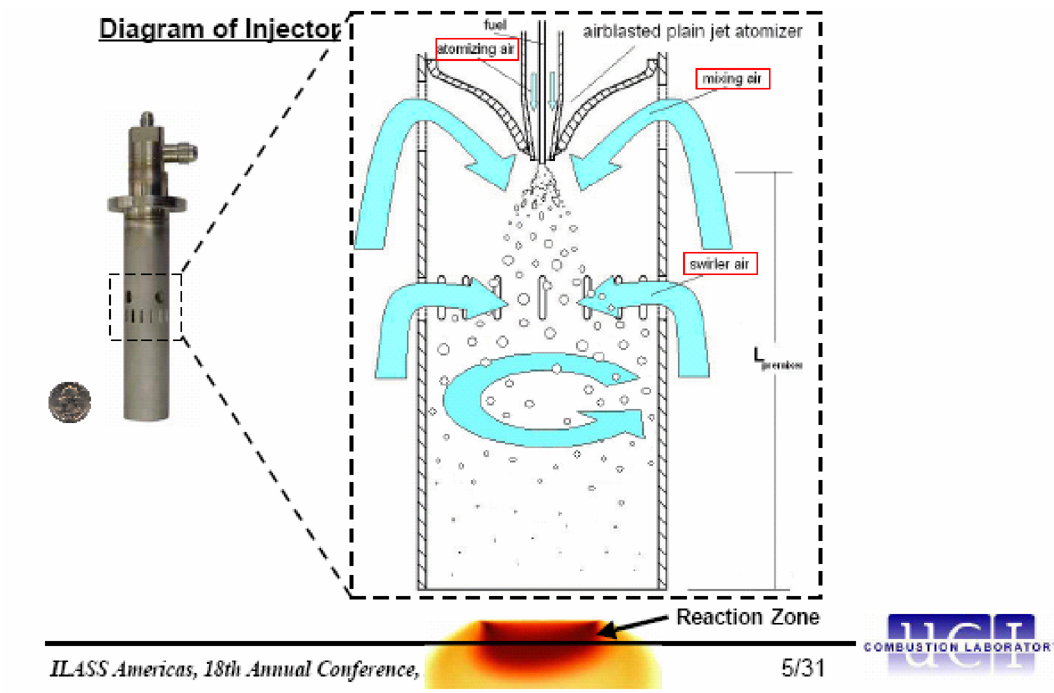

Figure 1. Picture of the Capstone Nozzle

It was initially intended to test the injector in the spray facility at BNL. The mixing tube was enclosed with inlet for the mixing and swirler airs and an attempt was made to measure the atomization characteristics. However, it became obvious that the spray geometry from the airblast atomizer was such that droplets were hitting the wall of the mixing tube and a portion was dripping from the vertical injector. This could not be avoided by almost any combination of fuel and air flows. In consultation with Capstone, it was decided to cut off the mixing tube from one of the injectors and proceed with testing the airblast atomizer by itself. The results compiled below are thus representative of what the drop size distributions are in the sprays as they emerge from the atomizer without any changes due to the air flows from the mixing tube.

The atomizer was set up vertically above an enclosure with openings to allow the laser incident and diffracted beams clear access. This enclosure sits above a collecting drum and there is a small vertical downward current of air maintained in the enclosure. The set up including part of the Malvern System 2600 spray analyzer is shown in figure 2 below.

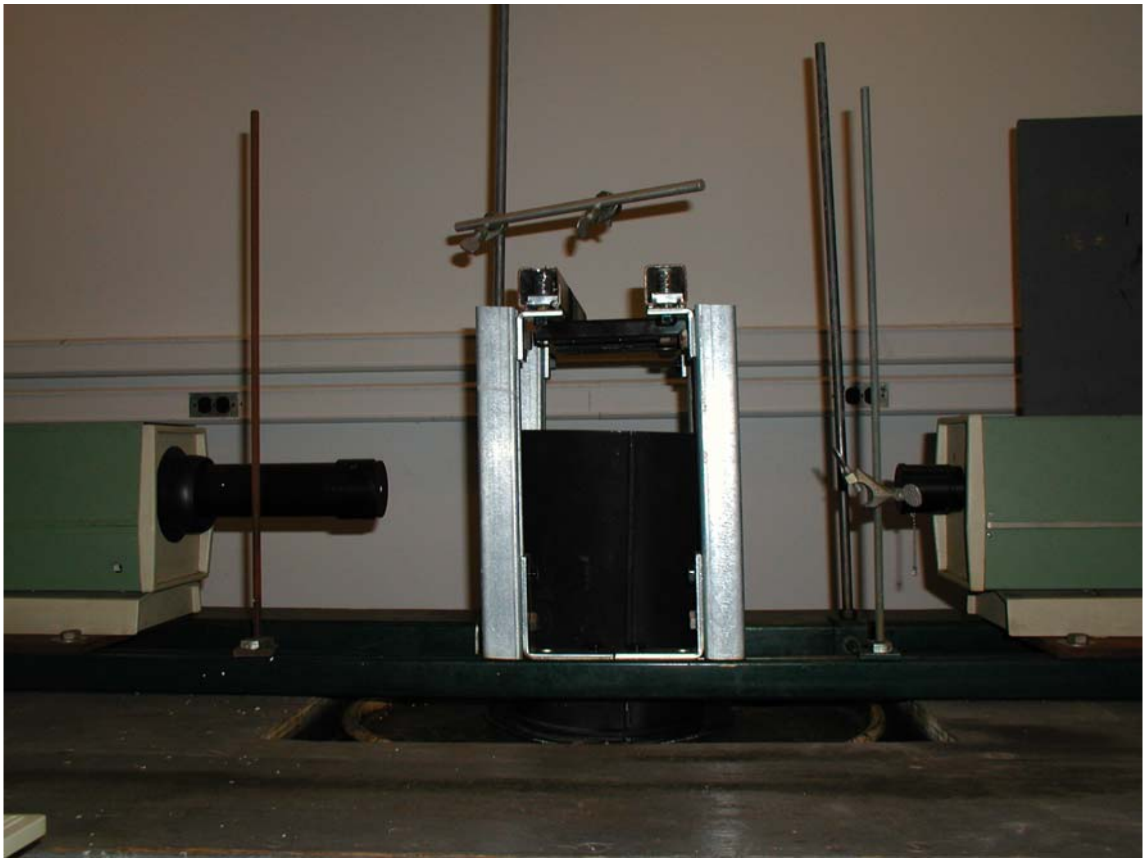

Figure 2. Malvern System 2600 Facility

The ‘fuels’ are delivered to the atomizer by a small solenoid pump with valves to regulate pressure and hence flow rate. The flow rate is measured by timing the weight change of the reservoir sitting on a scale. The laboratory air supply is connected to the atomizer through a pressure regulator and a rotameter to measure the flow rate of atomizing air. The data is acquired by the Malvern system using their so-called ‘model independent’ model. This helps to identify any potential ‘bi-modal’ distributions as will be noted below.

Four ‘fuels’ were tested. Water was used to establish the protocol and also gave a high surface tension fluid for the tests. This was felt to be important to check the correlation used, as there was not much difference between the surface tensions of the ASTM #2 oil and the biodiesel used for the blends. After the water tests, the #2 oil, B100 or neat biodiesel and a B50 blend were tested. The spray measurements were taken at two fuel flow rates that correspond to the low and high flow rates for the nozzle in the turbine. For each fuel flow rate, the air flow rate was varied over a range so that drop sizes could be measured over a range of atomizing air to fuel ratios.

Results and discussion

The test results are presented primarily as a series of graphs to highlight the differences, if any, between the different fuels. The Lefebvre correlation [1, 2] was tested against the data using physical data from the literature [3] and the dimensions for the nozzle exit diameters. The physical data, given in Table 1 below, for the fuels and blends and the nozzle dimensions were used in the correlation calculations.

Table 1.

Fuel	Surface Tension, mN/M	Viscosity, mPaS	Density, Kg/M^3
Water	72	1.0	1000
#2 fuel	23	3.5	855
B100	28	5.5	880
B50	25.5	4.5	867.5

Figure 3 below is a compilation of the volume mean diameter, D43, data for the four fuels at the low flow rate presented for a range of air to fuel ratios. It is seen that, as expected, the diameter reduces with increase atomizing air to fuel flow ratio. More importantly, it seems that the mean diameters are nearly the same at the same air to fuel ratio for all the liquids, suggesting that the variation in physical properties is not very significant in determining the volume mean diameter.

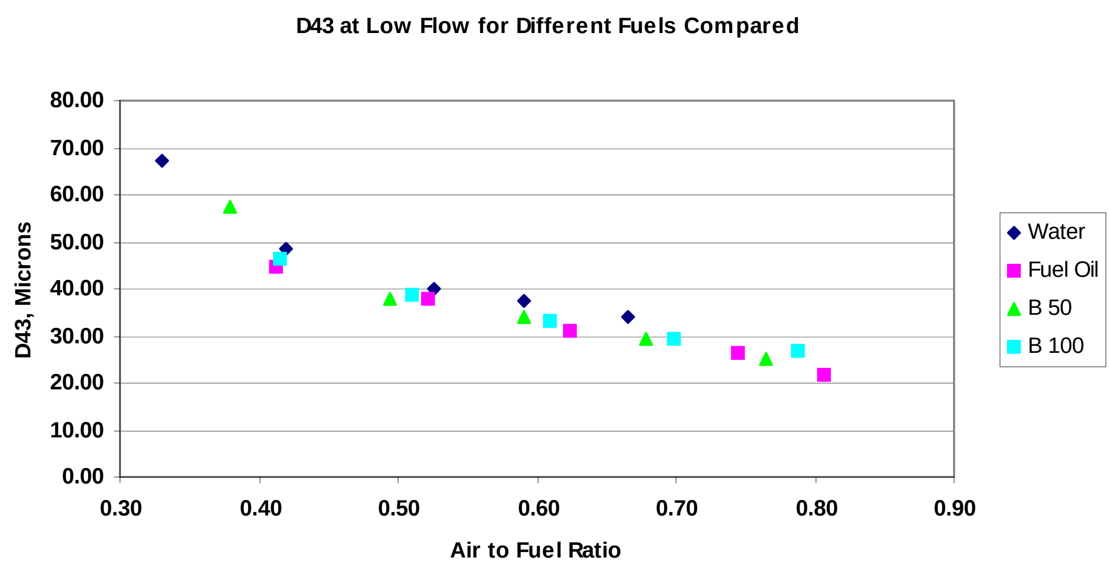

Figure 3. Volume Mean Diameter at Low Fuel Flow Rate

Figure 4 below gives the data on the Sauter mean diameter, D32, for the same conditions. In this case, the diameters for the water, neglecting the outliers for now, seem to be a little bit higher than for the other liquids which all have about the same surface tension. This suggests that the surface tension may be somewhat significant in determining the Sauter mean diameter.

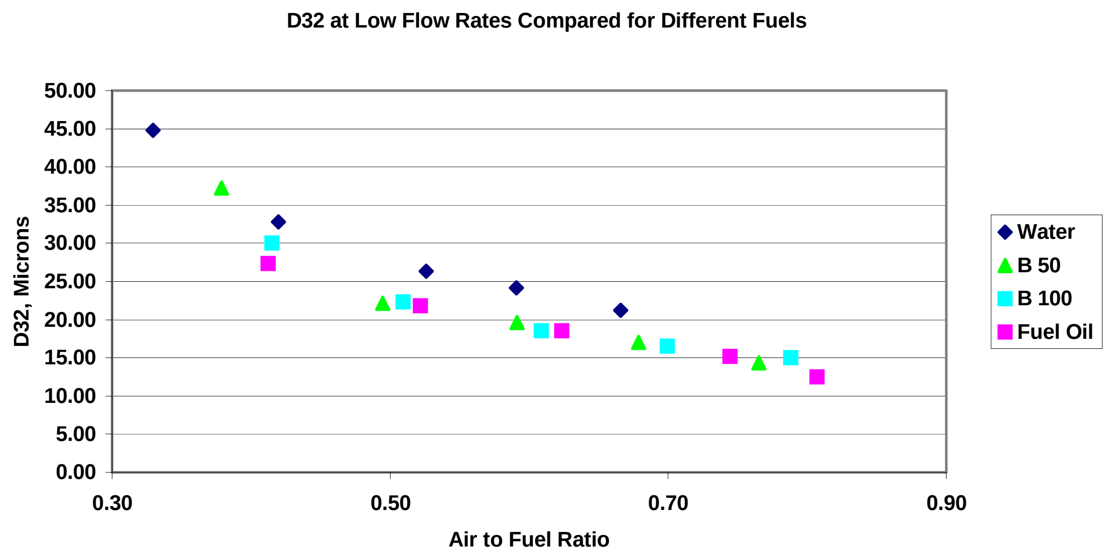

Figure 4. Sauter Mean Diameter at Low Fuel Flow Rate

Figures 5 and 6 below compare similar data for the four liquids at the high flow rates for the nozzle. It seems that, unlike at the low flow rate, the differences between the fuels are less for both the volume mean and Sauter mean diameters.

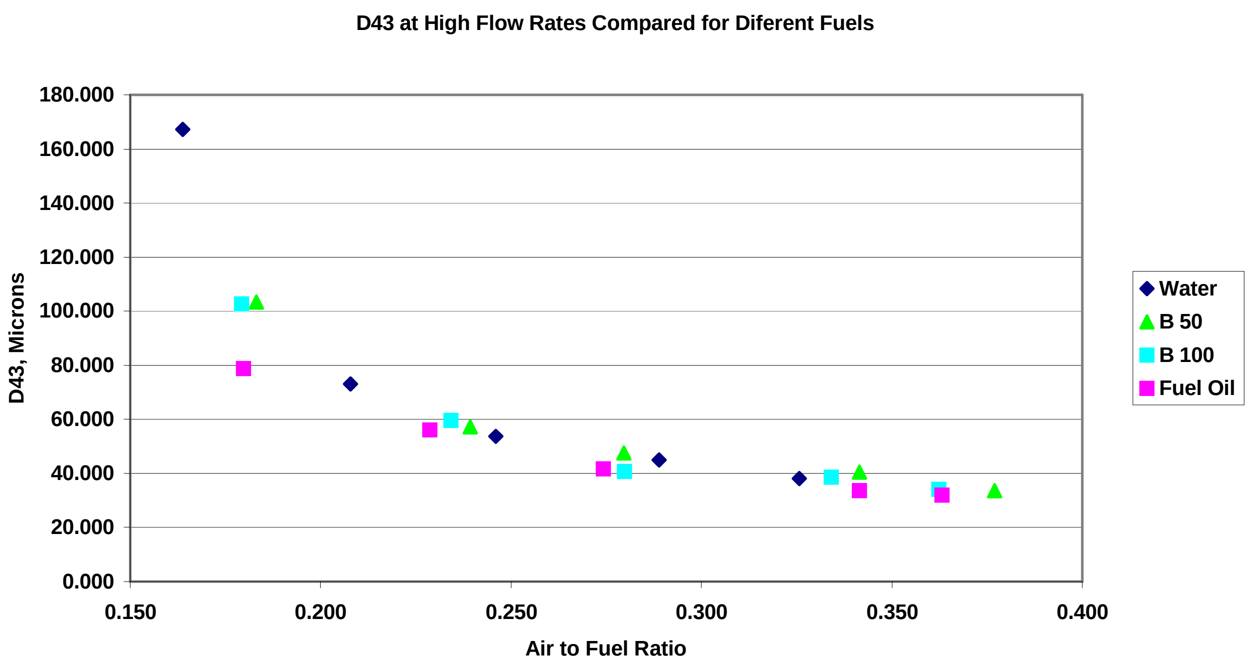

Figure 5. Volume Mean Diameter at High Fuel Flow Rate

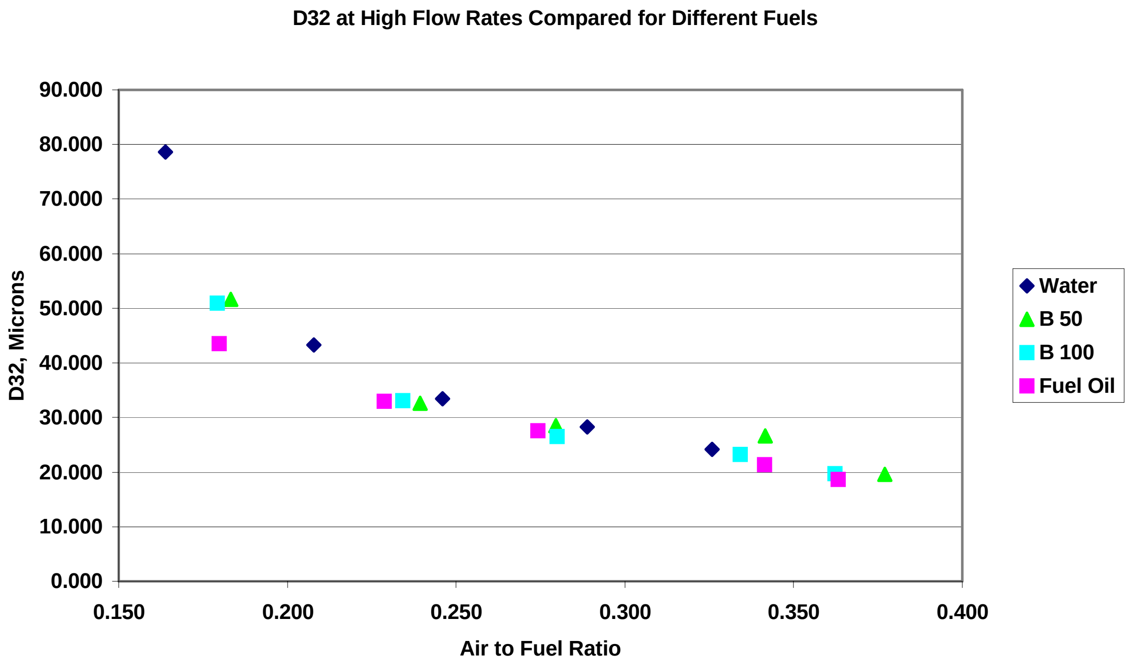

Figure 6. Sauter Mean Diameter at High Flow Rate

There are a number of empirical correlations that have been proposed for twin-fluid atomizers. The Lefebvre correlation [1,2] for the Sauter mean diameter, which is evaluated for comparison with the experimental data below, is as follows:

$$D32/D=0.48[\sigma/\rho U^2 D]^{0.4}\ [1+1/ALR]^{0.4} + 0.15[\mu_l^2/\sigma\rho_l D]^{0.5}\ [1+1/ALR] \qquad (1)$$

Where
σ is the surface tension of the liquid being atomized,
ρ is the air density,
U is the relative velocity between the air and the liquid,
D is the diameter of the liquid outlet orifice,
ALR is the ratio of the atomizing air to liquid flow rates,
μ_l is the liquid viscosity, and
ρ_l is the liquid density.

Figures 7 and 8 below compare the two mean diameters against the correlation above for D32, the Sauter mean diameter. It would seem that the correlation tracks more closely D43, the volume mean diameter rather than D32 with the parameters used here. Small changes in values for the physical parameters do not make a very significant difference. A sizable change in the 'reference' diameter D could make the correlation track the data for D32 better.

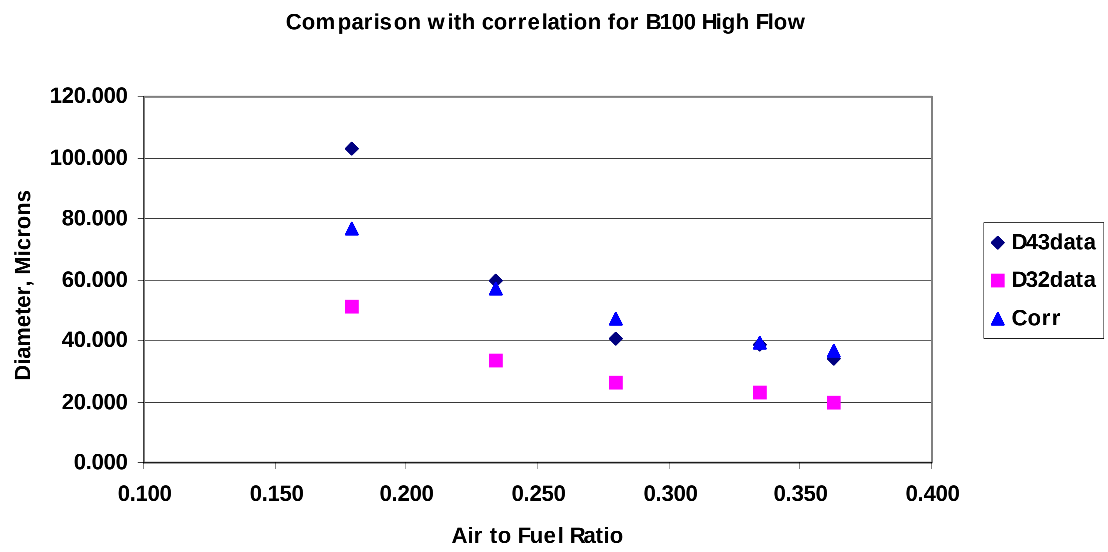

Figure 7. Comparison of B100 High Flow Data with Correlation

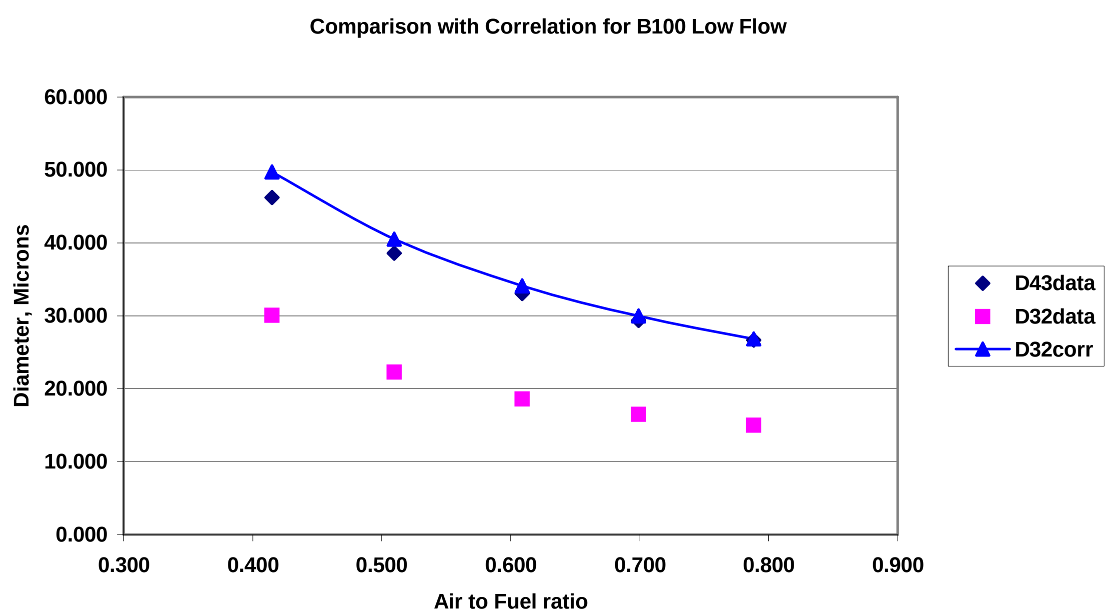

Figure 8. Comparison of B100 Low Flow Data with Correlation

Figures 9 and 10 below show corresponding comparisons for the #2 fuel oil and the tracking of the correlation with D43, the volume mean diameter, is much better as mentioned above.

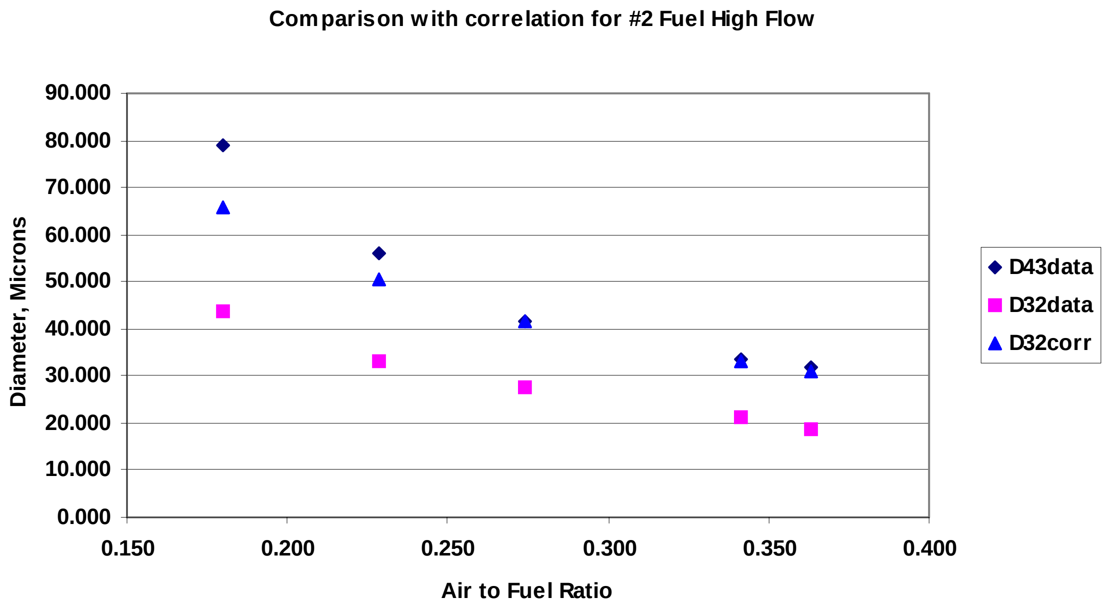

Figure 9. Comparison of #2 Fuel High Flow Data with Correlation

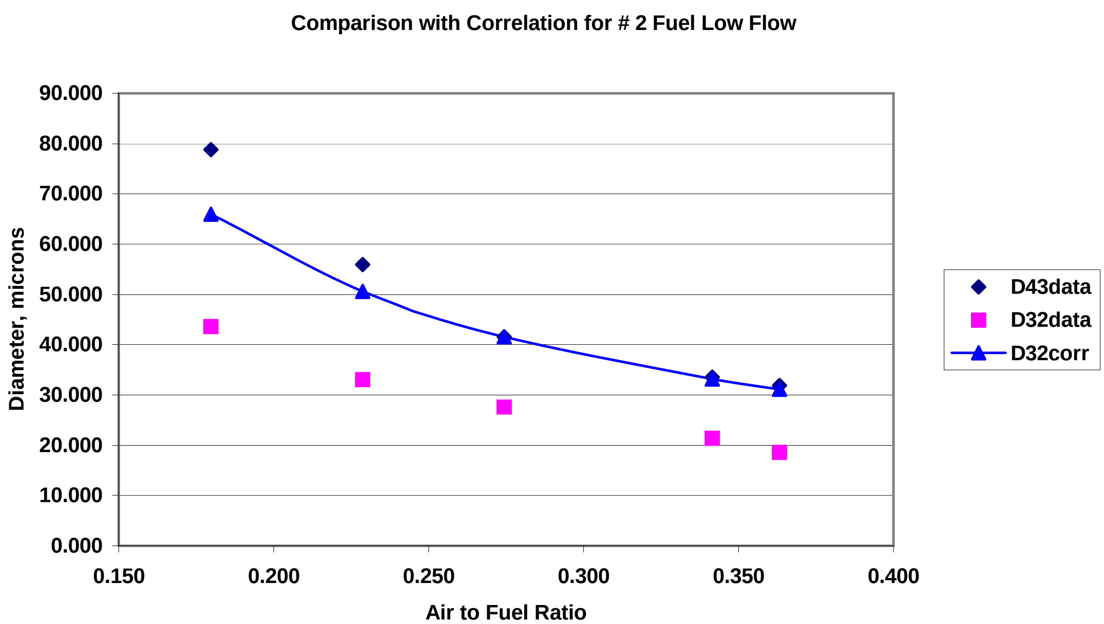

Figure 10. Comparison of #2 Fuel Low Flow Data with Correlation

For the combusting spray, not only the mean diameters but also a measure of the largest diameter, could be important. The Malvern data output includes a parameters to quantify the latter in a way by the diameter under which 90% of the volume is and is designated D [v,0.9]. This diameter is plotted in figures 11 and 12 below for the two flow conditions and for all the liquids tested. Some obvious observations from the data are that *a.* there is not much difference between these liquids for the 'maximum' diameter and *b.* the diameter can be quite high at the high flow (and low air to liquid ratio) conditions. These diameters could control final burnout in the combustion chamber, as well as be significant for emissions such as soot and NOx, as large diameter drops tend to support wake diffusion flames. Of course, in the Capstone microturbine, the atomizer spray is modified by the hot air/gas flows through the mixing tube and the data obtained here are not in themselves sufficient to present the full picture of how the injector performs in the combustor.

Digital pictures, still and brief video, were also taken of the sprays in the test rig. They can provide some qualitative information on the effect of the different fuels on the atomizer performance. For example, figures 13, 14 and 15 below suggest that that the spray tends to get wider as we go from fuel oil to water, which would be consistent with their increasing density.

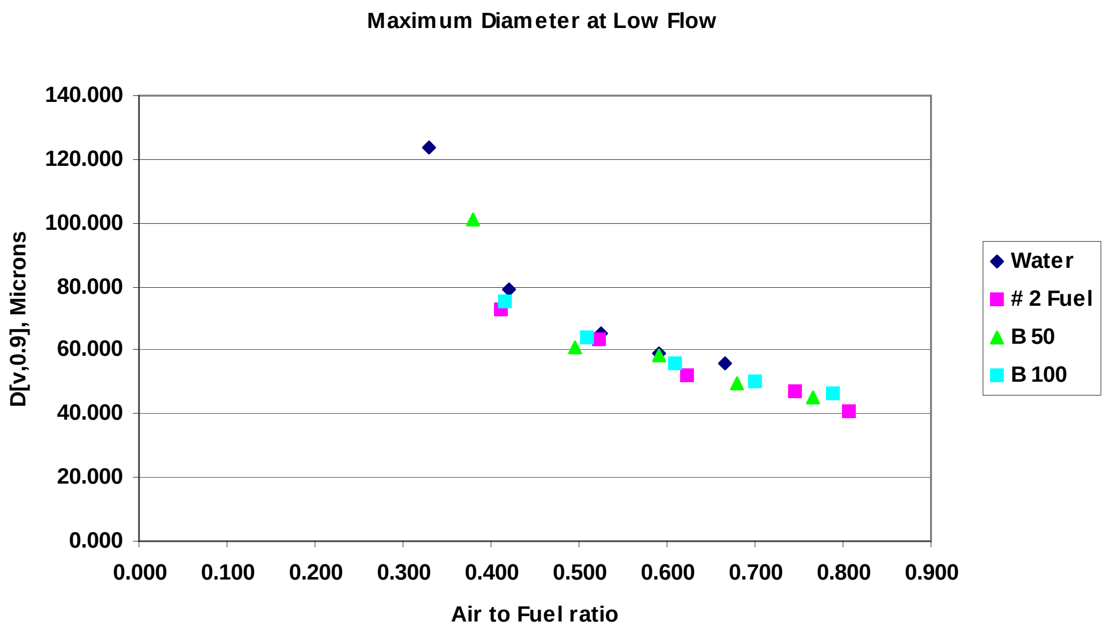

Figure 11. D[v,0.9] at Low Flow for All Liquids

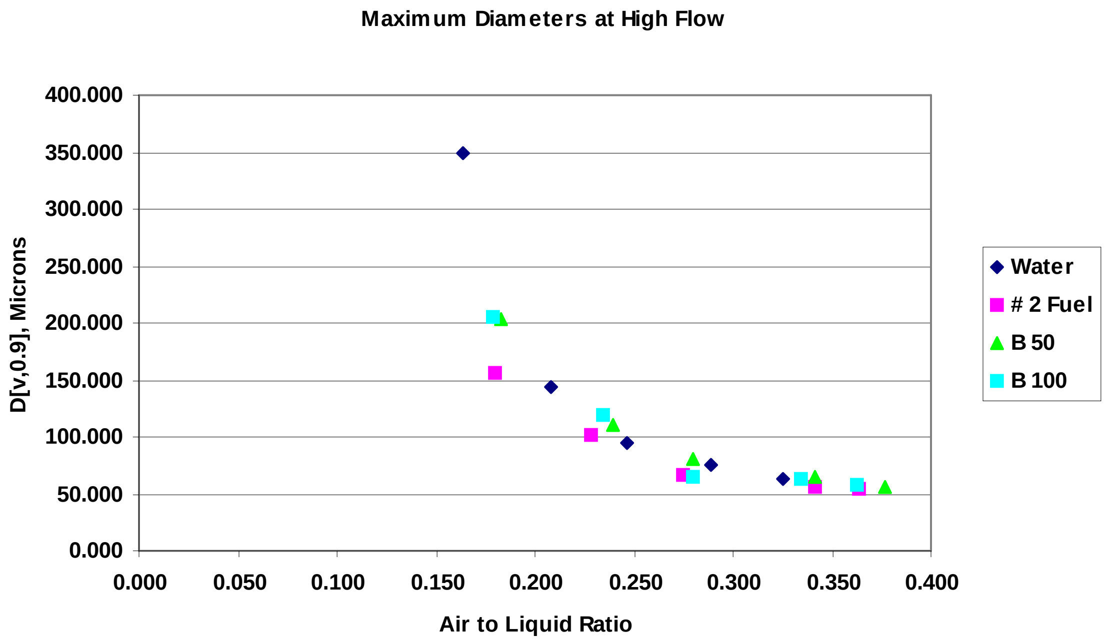

Figure 12. D[v, 0.9] at High Flow for All Liquids

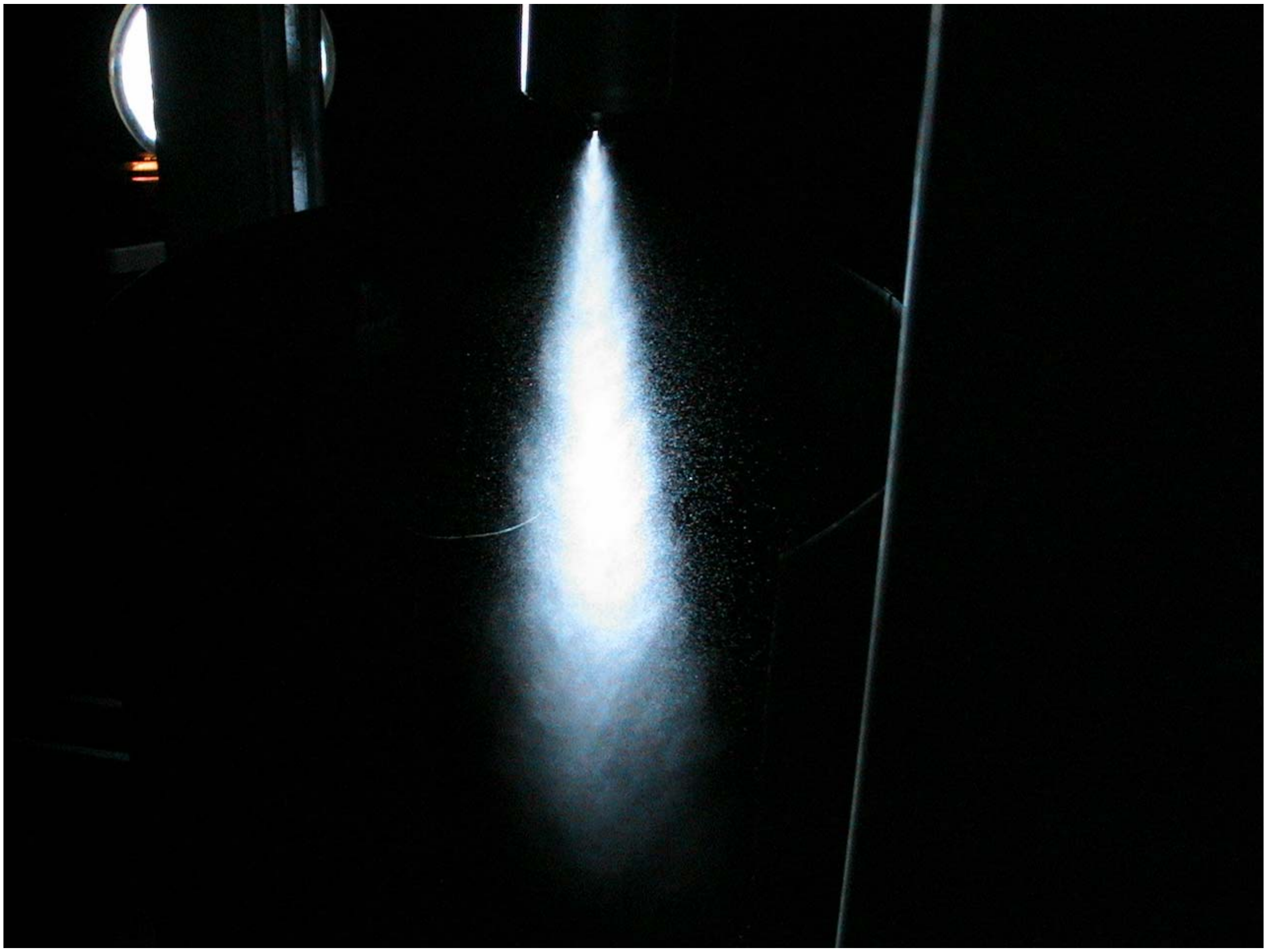

Figure 13. Photo of #2 Fuel Oil Spray at the Low Flow Rate

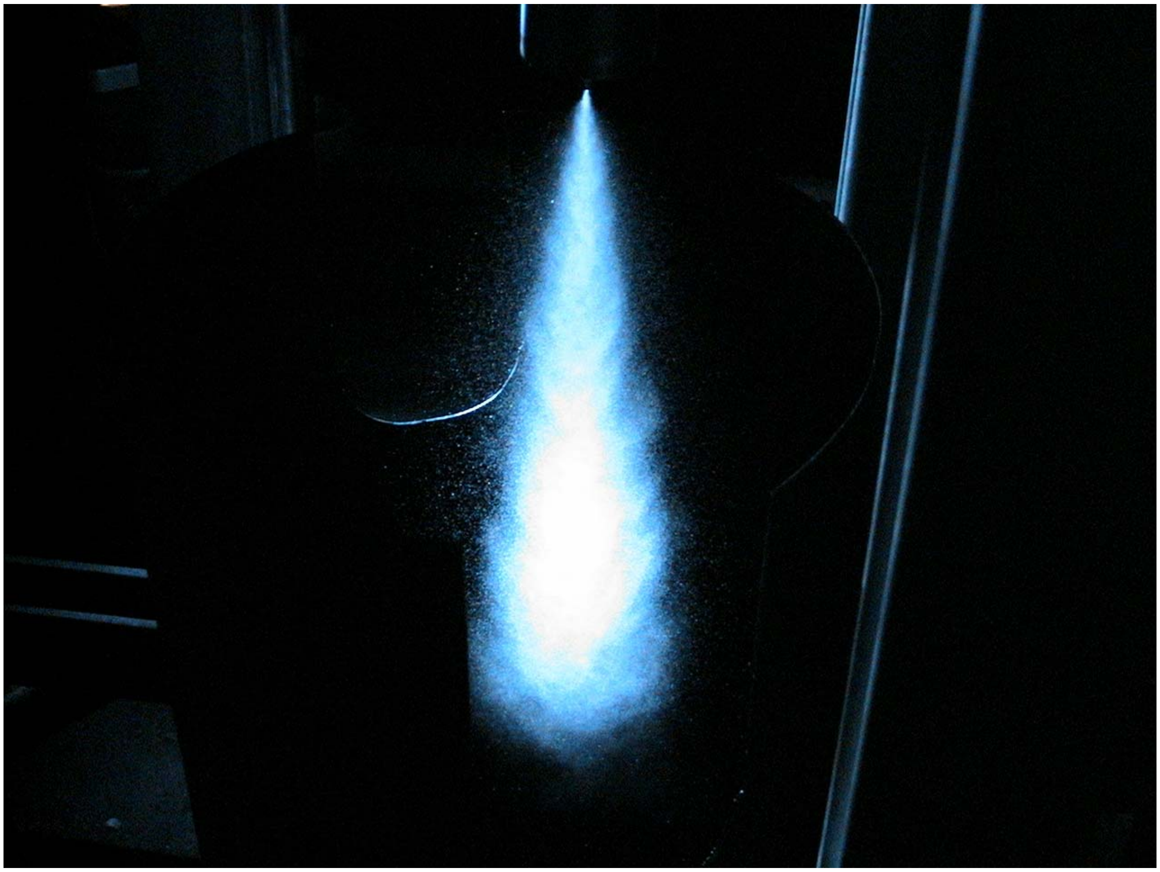

Figure 14. Photo of B 100 Spray at Low Flow Rate

Figure 15. Photo of Water Spray at Low Flow Rate

Conclusions

1. As is well known, the air to liquid flow rate ratio has the strongest effect on the mean drop sizes of the spray.
2. The effect of surface tension and viscosity, in the range of the fuels tested, on the mean diameters is not very significant.
3. The Lefebvre correlation, although intended for the Sauter mean diameter, seems to track much more closely with the volume mean diameter in the data obtained here. This seems to be unlike the conclusion in reference 1.

The maximum diameter, as inferred from the 90% volume data, is quite high at the high flow and under low air to liquid ratios.

Acknowledgements

George Wei deserves thanks for getting the atomizer ready for the tests and helping with the measurements. Tom Butcher is owed thanks for support throughout and for reviewing the report. The Department of Energy is acknowledged for funding the project, with thanks to Don Geiling as the project manager. Thanks to Don Geiling and Debbie Haught at the Department of

Energy, who have both been encouraging and supportive. Steve Gillette and Craig Smugeresky of Capstone Turbine Corporation have been very helpful with material and technical support.

References

1.C.D. Bolszo, J.L. Mauzey, & V.G. McDonell and S. Nakamura, "Experimental Investigation of Liquid Fuel Atomization, Mixing and Pollutant Emissions for a 30kW Gas Turbine Engine," ILASS Americas, 18th Annual Conference, Irvine CA, 2005.
2. Adel Mansour, and Norman Chigier, "Air-blast atomization of Non-Newtonian liquids," J. Non-Newtonian Fluid Mech., 58 (1995) 161-194, 1995.
3. K.C.Watts**,** and Roxanne E. Tate**, "**Experimental Determination of the Density, Viscosity, and Surface Tension of Three Commercial Biodiesel Fuels up to 300^0C," Written for Presentation at the CSAE/SCGR 2005 Meeting, Winnipeg, Manitoba, 2005.